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Physics Procedia 5 (2010) 101–108
Physics Procedia
www.elsevier.com/locate/procedia

LANE 2010

Variable disk laser for optimized micro machining

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Invited Paper

Abstract

Since many years shortening of pulse duration down to femtosecond regime is propagated as a recipe for achieving higher precision in micro machining with lasers. The drawback of this approach is a loss in productivity which cannot be accepted when large work pieces such as rolls, cylinder liners or solar panels have to be treated. A novel development tool based on disk technology will be presented allowing finding application specific highest productivity at still acceptable inaccuracy.

Keywords: Micro machining; precision; productivity; ultrafast lasers; femtosecond; disk laser; regenerative amplifier

1. Introduction

While depth and width of pockets, grooves or holes produced with pulsed lasers remain in the range of micrometers, the dimension of the work-piece surfaces to be treated range into centimeter and even meter region quite often. Examples are tribologically active structures on engine components such as cylinder liners, rolls for deep printing, embossing and extrusion, flat panel displays and solar panels. It is evident that in such applications laser techniques can compete economically with conventional ones only if the achieved quality can be reached at sufficiently high

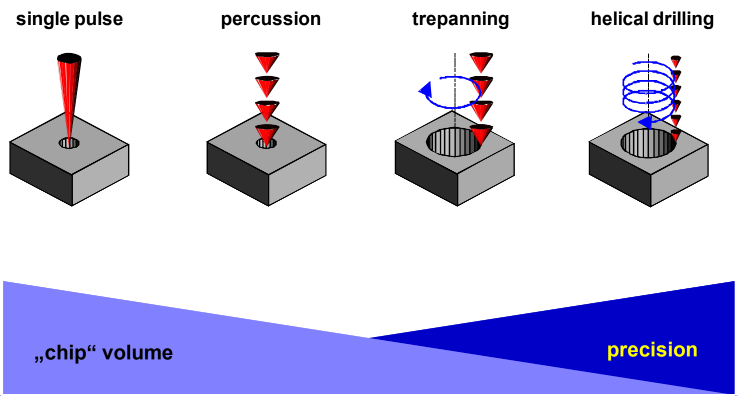

Fig. 1. Comparison of processing strategies in terms of their potential for high accuracy laser drilling

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doi:10.1016/j.phpro.2010.08.126

productivity. The universal conflict between accuracy and productivity, however, is encountered in laser processes as well. This is illustrated in figure 1 for drilling: In single pulse drilling several hundred holes per second can be drilled through 1 mm of steel, in helical drilling several ten thousands of pulses are needed to penetrate the same depth. In the first case the hole geometry with rounded entrance edges and large diameter tolerance is good enough for particle filtering. The sub micron accuracy demands of fuel injection nozzles can be reached with helical drilling, only.

2. Optimizing accuracy and productivity

2.1. Increase of accuracy

In micro machining with lasers not only the removed ("chip") depth influences accuracy but also its physical state. In liquid state material can be removed most efficiently but mostly not totally leaving behind recast layers and burr. Vaporization without melting (sublimation) would deliver highest accuracy at the expense of more energy consumption, is however only feasible for some materials which do not form melt. For the majority of materials sublimation can be approached by increasing intensity and thus reducing the share of melt in the removed matter, only. If, however, intensity is high enough to ionize the ablated material, the machining tool's sharpness might be reduced by extending the beam-matter interaction in space and time.

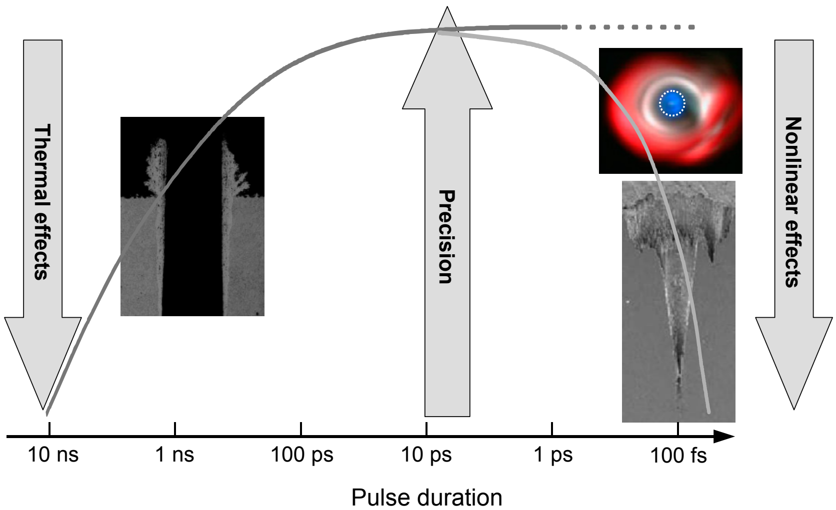

Fig. 2. Schematic illustration of the achievable precision level in drilling of metals depending on laser pulse duration

A well accepted way to reduce ablated depth per pulse is the reduction of pulse duration. The idea behind this approach is to eliminate heat conduction and thereby reduce the heated depth to the optical penetration depth which in metals is in the order of a tenth of the laser wave length. It turned out that in metals a maximum in accuracy is reached in the short picoseconds range already, see figure 2 [1]. Because of the physical nature of energy transfer from laser beam to matter the thermal interaction time cannot be reduced further. On the other hand non-linear plasma effects at sub picoseconds pulse duration might blunt or even destroy the machining tool, see figure 2.

Dielectrics, on the other hand, are mainly transparent in a large range of wave lengths from visible to near infrared. This opens an efficient way to reduce the "chip" depth and width by using non-linear absorption. At the high intensity level of femtosecond pulses multi-photon absorption becomes possible creating start electrons for a following avalanche process leading to strong absorption. The creation of the non-linear absorption coefficient α_{nl} scales like

$$a_{nl} \sim E^k$$

with k being the number of photons necessary to bridge a band gap which is typically 3 to 4. The strong dependence on intensity E enables not only a precise localization of the absorbing volume along the beam axis by positioning the plane of focus on top or inside of a transparent matter but also a reduction of the lateral dimension to a fraction of the diffraction limit.

The localization of the plane of ablation inside a transparent material is used for the frequently used Femto LASIK technique enabling refractive surgery of eyes without the need to use knives. For removal of technical materials like diamond it was shown, that the strong reduction of the optical penetration depth by shortening the pulse duration from some picoseconds to about hundred femtoseconds leads to a significant increase of precision by avoiding bulk heating [2].

In laboratories it was demonstrated that a reduction of lateral structure size below 100 nm is possible even with NIR wavelength. A technical application of this effect has to be developed, intensive research activities have been started already.

2.2. Increase of productivity

In general all measures discussed in the previous section reduce productivity. There are, however, some ways to increase productivity while maintaining accuracy [3]:

- increase of laser power by increasing repletion rate,
- parallel processing with splitted beam,
- enlarging interaction zone,
- using shorter wave length to avoid disturbing plasma effects.

Figure 3 illustrates the effect of reducing the laser wave length in drilling of 1 mm thick steel [4]. The left boring was made with 1064 nm, the right one with 532 nm. In both cases the same pulse energy of 80 µJ and repetition rate of 40 kHz was used. With the green wave length the drilling time could be reduced by a factor of 2. The increase in process efficiency therefore totally compensated the loss in laser efficiency caused by frequency doubling. The crucial point is, however, that in case of green laser light the hole geometry followed the beam geometry nearly perfectly whereas in the infrared case an unwanted broadening near the focal plane was observed which is presumably caused by plasma.

In cases where the mentioned measures do not help to achieve the required productivity one should carefully check to which extend a loss in accuracy is acceptable and try to find a trade-off allowing economic production. For this purpose a flexible laser system allowing varying the key parameters pulse duration and wave length is highly beneficial.

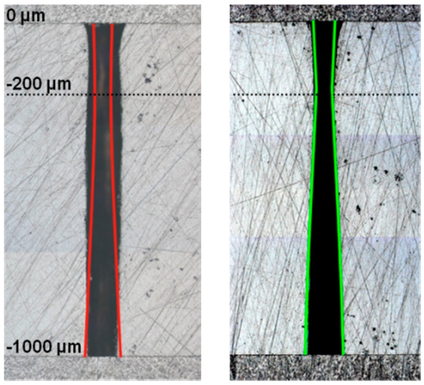

Fig. 3. Drilling with IR (left) and green wavelength

3. The disk laser

3.1. General advantages

Thin disk laser technology [5] has been developed since early 1990s and is now mature for industrial applications. The technology uses a disk-shaped laser material with a thickness of several tenths of mm. This allows efficient heat evacuation and thus high power output with a good beam quality. So far 25 kW of laser power with a beam quality “suitable for a tactical weapon system” was demonstrated in continuous-wave operation [6]. Commercially cw multimode lasers are available up to 16 kW. In that case 4 kW are extracted from one disk.

For pulsed lasers and especially for ultra-short pulse lengths the thin disk geometry is particularly suitable since the size of the laser mode on the disk can be nearly freely chosen. So the pulse damage can be avoided simply by enlarging of the beam size on the disk enabling very high pulse energies. For ultra short laser pulses the small amount of the laser material crossed by the laser beam is an additional advantage. Dispersion and non-linear effects in the laser disk are negligibly small.

Stress induced birefrigence is also negligibly small because of the small amount of material. The depolarization ratio is typically far below 1 % allowing for highly efficient operation of the disk laser with polarized output. This is particularly important for pulsed lasers because typically a Pockels cell switch is used in pulsed operation.

3.2. Pulsed operation modes

Most of known pulsing techniques can be used within the disk laser technology. Table 1 shows what major components are necessary to build a pulsed disk laser operating in the given pulsed mode.

Table 1. Components of pulsed disk lasers in different operation modes

	disk module	pump diode	Pockels cell	seed laser	compressor
regenerative amplification with dispersion compensation	+	+	+	+	+
regenerative amplification	+	+	+	+	-
cavity dumping	+	+	+	-	-
Q-switching	+	+	+	-	-

Mode locking technique is not included, because it is not in the scope of this paper. A good review is given in [7].

All pulsed lasers in the Table 1 were already realized in the laboratory with output powers exceeding 100 W. They all require a gain element represented by the disk module and the pump diode, which delivers energy to the laser. The Pockels cell can be sometimes substituted by another optical switch. Especially in the case of Q-switching acousto-optical modulators (AOM) are broadly used. For other techniques the switch time of AOMs is typically too long.

For a regenerative amplifier additionally a seed laser is necessary. The seed laser defines the temporal and spectral shape of the output pulse except for the case of pulses shorter than the gain-bandwidth. Using of a compressor allows to compress the pulses after amplification and to extend the pulse duration range to sub-picosecond pulse durations.

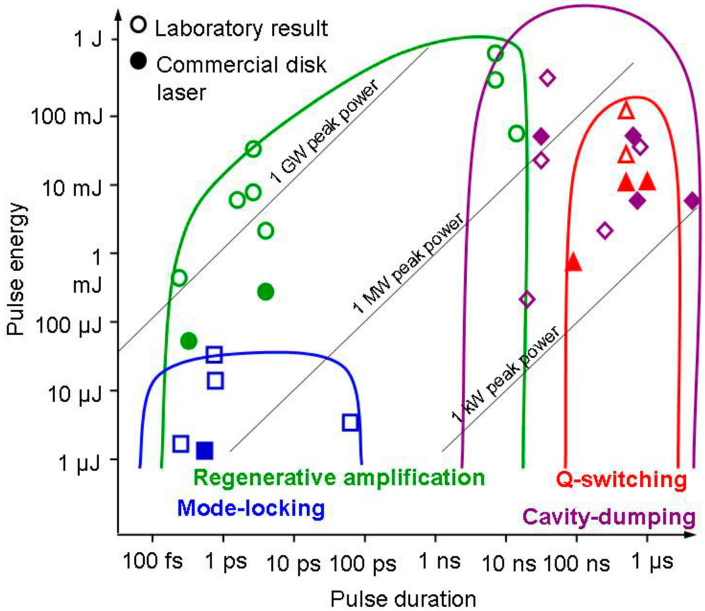

Fig. 4. Pulse energies demonstrated with thin disk lasers using different pulsing techniques in laboratories and in commercially available products

In Fig. 4 results demonstrated with thin disk lasers in different pulsed operation modes are summarized. The graph was shown in [8] first and was updated by the authors. The solid lines show the possible pulse durations and expected pulse energies using different pulsing techniques. Practically the whole range of pulse durations between sub picoseconds and microseconds can be covered using the pulsing techniques described in Table 1. All the components necessary to realize these pulsing techniques are already included in the most complex set-up of the femtosecond laser – a regenerative amplifier with dispersion compensation. So just by using another seed source or by changing of the electrical control of the Pockels cell the laser can produce a very broad spectrum of pulse durations. In the following subsections the used pulsed techniques will be described in more detail.

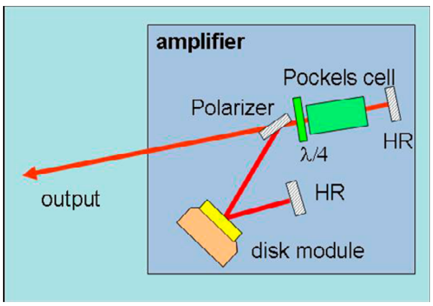

Fig. 5. Set up for Q-switching and cavity dumping

Q-switching

For Q-switching only the amplifier cavity with disk module and Pockels cell are necessary (Fig. 5). The non-zero output coupling during amplification, which is the specific feature of Q-switching, is realized by reducing of the high voltage applied to the Pockels cell during the on-time to a level lower than the λ/4-voltage.

Due to the long pulse build-up time typical for thin disk lasers operated in Q-switched mode, the repetition rate is limited to about 20 kHz with sub-microsecond to microsecond pulse duration. The pulse energy is limited only by the damage of the disk or cavity mirrors. The laser can be safely operated up to pulse energy of 20 mJ.

Cavity dumping

Cavity dumping is very similar to Q-switching. The set-up is the same as shown in Fig. 5. On contrary to Q-switching the voltage applied to the Pockels cell during the on-time is exactly the λ/4-voltage. The amplifier cavity does not have induced losses during the on-time of the Pockels cell. The energy caught in the cavity increases and is dumped by switching off the Pockels cell. The length of the output pulse is determined by the length of the cavity.

Thin disk lasers are preferably operated in cavity dumped mode at repetition rates exceeding 100 kHz because of the absence of the pulse energy bifurcations at higher repetition rates. The typical pulse duration is determined by the practically used cavity lengths and is between 10 ns and 20 ns.

Longer pulses can be produced if the Pockels cell is switched off either with a long switch-time or it is switched firstly to some intermediate voltage and afterwards to zero. In this case the energy stored in the cavity is dumped slower, during several round trips, producing pulses with pulse duration electrically adjustable from 10 ns to several hundred of nanoseconds.

Regenerative amplification

The set-up of a regenerative amplifier is shown in figure 6. The pulse duration of the seed laser determines the pulse duration of the output pulse. For short pulse durations this is true for pulse duration >4 ps and for long pulse durations the pulse length is limited by the length of the cavity to approx. 10 ns.

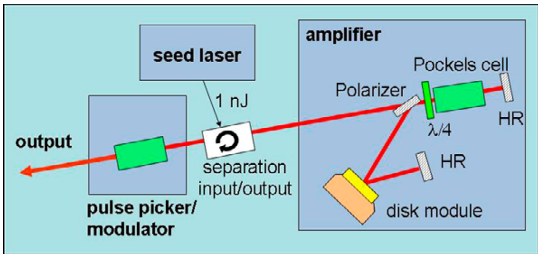

Fig. 6. Set-up of a disk regenerative amplifier

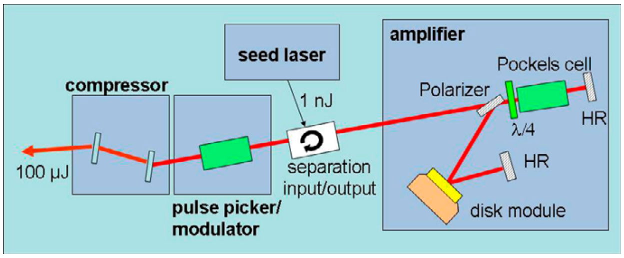

Fig. 7. Set-up of a disk regenerative amplifier with pulse compression

Any seed source with appropriate spectrum centered at 1030 nm, enough pulse energy (>1 nJ) and a repetition rate lower than 50 MHz can be used. For the fiber-coupled seed source the seed source can be changed by connecting of another fiber-coupled source. Seed sources with free space output can be placed inside the laser with a mechanical or optical switch defining which of the seed sources is used currently.

The pulse energy is limited in the described set-up by pulse damage in the amplifier. More than 10 mJ have been demonstrated in the short picosecond range and several hundred µJ in the femtosecond range, see figure 4. Enlarging of the mode size allows higher pulse energies but decreases the flexibility and the reliability of the system. The repetition rate is limited by the Pockels cell driver which is capable of operation at maximum 1 MHz.

Regenerative amplification with dispersion compensation

The usage of a compressor allows an additional degree of freedom – the dispersion of the pulses can be overcompensated. This allows for adjustment of the pulse duration from sub-picoseconds to about 8 ps just by changing of the distance between the diffraction gratings.

4. A flexible disk laser set up

A laser like the one described in figure 7 has been realized using a mode-locked seed laser with pulse duration of 200 fs and pulse energy of 4 nJ at a repetition rate of 40 MHz. The seed laser is an oscillator without a post-amplifier, which is not necessary. This makes the seed laser less sensitive to back reflections, often occurring in master-oscillator-power-amplifier (MOPA) design.

The pulses of the seed laser are coupled in the thin-disk amplifier through the separation unit. No stretcher is used because pulse damage can be avoided simply by choosing of the correct mode size on the laser disk and other optical components. This makes the laser less complex and more reliable.

The amplifier is a stable cavity with a disk module, a Pockels cell and a retardation plate (λ/4) inside. The disk module implements an Yb:YAG disk with a thickness of 0.215 mm and 7 % doping concentration and a multipass pump optics, which realizes 24 passes of the pump radiation through the disk allowing for the efficient absorption of the pump radiation. Pump radiation with a wavelength of 940 nm is transported to the disk module by a fiber. If the Pockels cell is off (no high voltage) the retardation plate rotates the polarization of the seed pulse by 90° after two passes and the seed pulse is reflected at the polarizer towards the disk module. After one complete round trip of the amplifier the pulse is coupled out after the next two passes through the retardation plate. If the Pockels cell is switched on, while the pulse is in the cavity, then the pulse remains in the cavity for the on-time of the Pockels cell and is amplified.

Due to dispersion occurring in the Pockels cell the pulse duration increases during amplification, reducing the not desired nonlinear effects and eliminating pulse damage. The typical pulse duration after amplification is about 2 ps. The dispersion can be compensated with a pair of diffraction gratings. So far pulses with duration of 800 fs were demonstrated at a power level of 25 W and pulse energy of 83 μJ. Increasing of the power to 50 W and of the energy to 250 μJ mainly by increasing of the pump power from 150 W to 250 W is scheduled for this year.

The pulse duration of 800 fs is limited by the gain bandwidth of Yb:YAG. However nonlinear effects in the Pockels cell and spatial hole burning in the disk allows to produce output pulses with broader spectrum and shorter pulse duration as already shown for Yb:KLW (KLu(WO4)) [9].

The output spectra measured for different pulse energies in Fig. 8 shows clear broadening for higher pulse energies. The spectrum width increases from 3 nm to 4.5 nm, making producing of pulses with pulse duration of 500 fs feasible.

Broadening of the spectrum by spatial hole burning and/or self phase modulation depends on the output energy, making the output pulse duration depending on the pulse energy. In order to adjust the pulse energy by the given pulse duration the laser is operated with the pulse energy which is necessary to produce the desired pulse duration. The output pulse energy is reduced by the modulator to the desired level. The modulator is a second Pockels cell in the laser. The high-voltage driver of the modulator is in principle capable for pulse to pulse changes of the output pulse energy, enabling creation of user-defined pulse trains, which can be interesting for application.

All the components necessary to realize the pulsing techniques described above are already included in the set-up of the femtosecond laser. So just by using another seed source or by changing of the electrical control of the Pockels cell the laser can produce a very broad spectrum of pulse durations.

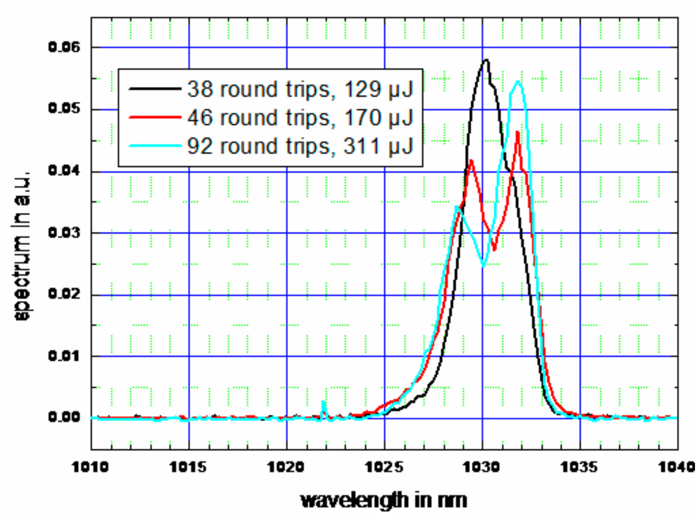

Fig. 8. Spectra of the output pulses measured with different numbers of round trips and output energies

5. Conclusion

The paper describes a disk laser system capable for an output power of 50 W with repetition rates between 100 kHz and 1 MHz, a pulse energy of maximum 250 μJ and a pulse duration of 500 fs. So far an output power of 25 W with repetition rates between 100 kHz and 300 kHz and pulse duration of 800 fs was demonstrated. It is shown that pulses with pulse durations between hundreds of femtoseconds and microseconds can be produced with this laser system by changing of the electrical control of the Pockels cell or exchanging of the seed source.

The laser produces a sufficient average power and energy for micromachining applications within a very broad range of pulse durations. It is, therefore, a very flexible tool for the development of micromachining applications, especially for optimization of precision and productivity.

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